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HIGH di/dt THYRATRONS

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## DEVELOPMENT AND EVALUATION OF SYSTEMS FOR CONTROLLING PARALLEL HIGH $di/dt$ THYRATRONS

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### Abstract

Increasing numbers of high power, high repetition rate applications dictate the use of thyratrons in multiple or "hard parallel" configurations to achieve the required rate of current rise,  $di/dt$ . This in turn demands the development of systems to control parallel thyatron commutation with nanosecond accuracy. Such systems must be capable of real-time, fully-automated control in multi-kilohertz applications while still remaining cost effective. This paper describes the evolution of such a control methodology and system.

Three techniques to control thyatron commutation have been examined and tested resulting in the development of a computer-controlled system. By proper correlation of trigger time and amplitude, three thyratrons have been operated in hard parallel with a common 10  $\Omega$  PFN and load up to 1500 pps. The discharge circuit and controls have operated over  $10^8$  shots without faults. Load current jitter has been maintained to  $\pm 2$  ns at the 25 kV 10  $\Omega$  operating point with little or no change in current sharing with changes in repetition rate. This characteristic lends itself to applications requiring forms of pulse modulation. The proposed control circuitry uses currently available off-the-shelf analog and digital components to keep system costs low.

### Summary

As reported a year ago,<sup>1</sup> two low-inductance HY-3103 thyratrons were operated in "hard parallel" in a 25  $\Omega$  modulator circuit at repetition rates to 250 pps. This was accomplished by adjusting the negative grid bias (thus the anode delay time) to force the thyratrons to commutate at the same time. This method allowed the use of a single source to trigger both tubes, thus reducing jitter. A common driver may also reduce the cost, particularly in a multiple-tube circuit.

Adjusting the negative-grid bias affects more than just the anode delay time, as recovery, anode falltime, and field grading within the tube also change. Controlling commutation in this manner proved possible but at high repetition rates these characteristics made operation very unstable and adjustments critical. A bias update rate of several times a second was found necessary to maintain control, requiring very high-speed analog and digital circuitry. It was decided to investigate the characteristics of each tube separately to see if any parameter could be identified as causing the instability before trying other control methods.

### Tube Characterization

The first measurement made was dynamic breakdown voltage vs reservoir voltage (tube pressure) and the graphical results are shown in Fig. 1. Both thyratrons were new and operated in the same resonant charged modulator circuit when taking these data. At first glance, it appears that the tube pressures are different. Conversations with EG&G engineers revealed that hydrogen fill pressures have better

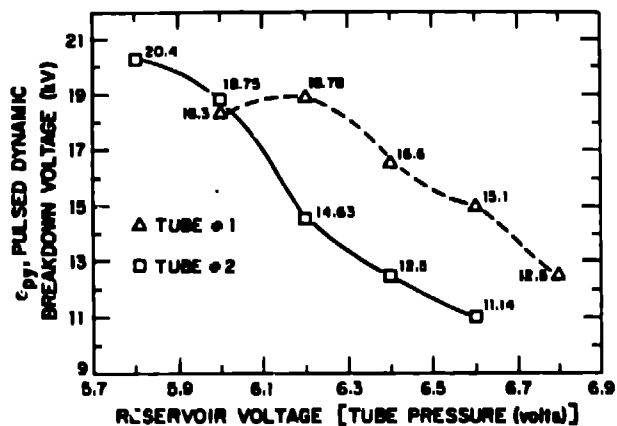


Fig. 1. Dynamic breakdown voltage vs reservoir voltage.

than 1% accuracy; however, the grid-anode spacing may vary up to  $\pm 20\%$ . Thus it is the "d" term of the Pd product causing the difference in breakdown voltages. The small difference between grid-anode spacing which may be acceptable in a single tube circuit has a drastic effect when thyratrons are operated in parallel. Further measurements were made to observe the differences in anode or commutation delay vs reservoir voltage between the tubes. As expected, the tubes were quite different in this respect, but the delay was linked loosely to the tube's dynamic breakdown.

The reservoir voltages for the two thyratrons were adjusted to closely match the commutation delays and the thyratrons were reconnected in parallel. This modification improved the circuit stability considerably, allowing operation of the modulator at up to 1000 pps at rated thyatron voltage. The requirement for frequent bias adjustments was found to be relaxed somewhat, reducing the need for high speed controls.

Even though the instabilities were reduced, the negative bias adjustment was still very critical, requiring an absolute accuracy of better than  $\pm 250$  mV. Further experiments with reservoir pressure, trigger amplitude, and bias control led to the conclusion that direct adjustments to the thyatron were too sensitive and affected too many of the tube characteristics to be of practical use.

### Trigger Delay Control

The next method of commutation control investigated provided separate triggers with adjustable delays to each of the thyratrons. The dynamic breakdown voltages of two new HY-3013s was determined and the tubes were installed in the parallel tube discharge circuit. Circuit parameters such as drive voltage, drive impedance, bias, etc. were identical. The anode delays were measured at test conditions for each thyatron and the trigger delays were set so that the thyratrons would commutate at the same time.

The thyratrons were brought up to rated voltage (25 kV resonant charge) and the tube currents were 250 amps peak each. Anode voltage was varied from 16 kV to 30 kV and the repetition rate from 100 pps to 1500 pps with less than 15% change in shared current amplitude. This method proved to be the most reliable and agile way of controlling parallel thyatron commutation. For a fixed anode voltage, the trigger delays would need adjusting a maximum of once an hour regardless of repetition rate. Continuous runs of 6 to 8 hours were common at rated thyatron voltage and 1000 pps.

All tests up to this point were done at a low peak current and thus low  $di/dt$ . Since good success was achieved with the individual trigger delay scheme, the next phase was to expand to three thyratrons and lower the discharge circuit impedance from 25  $\Omega$  to 10  $\Omega$ . A photo of the three-tube discharge circuit is shown in Fig. 2. Care was taken to reduce the discharge loop inductance and still limit the tube  $di/dt$  to  $10^{11}$  amps/sec. It had been found previously that when the  $di/dt$  in the HY-3013 was in excess of  $10^{11}$  amps/sec at 1000 pps, anode heating would cause the gas density (thus ion generation rate) to become sufficiently low to cause arcing in the grid-anode gap.<sup>2</sup>

A block diagram of the three-thyatron test circuit is seen in Fig. 3. Performance of the three-tube circuit was equal to or better than the two-tube circuit. Lowering the impedance from 25  $\Omega$  to 10  $\Omega$  did not affect the behavior of the thyratrons or the current-sharing stability. However, 10  $\Omega$  is still an order of magnitude higher than the impedance level ultimately needed. An oscillogram of the three tube currents and the load current is seen in Fig. 4. It should be noted that the load  $di/dt$  appears to be greater than the sum of the thyatron  $di/dt$ s. Because the effort of this program was to perfect a stand-alone system to operate thyratrons in hard parallel, the effect of  $di/dt$  enhancement was not investigated at this time. Current pulse parameters for both the two and three tube modulators are shown in Fig. 5.

#### Control Methodology

All development activities used Tektronix waveform digitizers to provide the nanosecond time resolution needed to control thyatron commutation. The thyratrons would current share if the commutation of



Fig. 2. Three parallel thyatron test circuit.

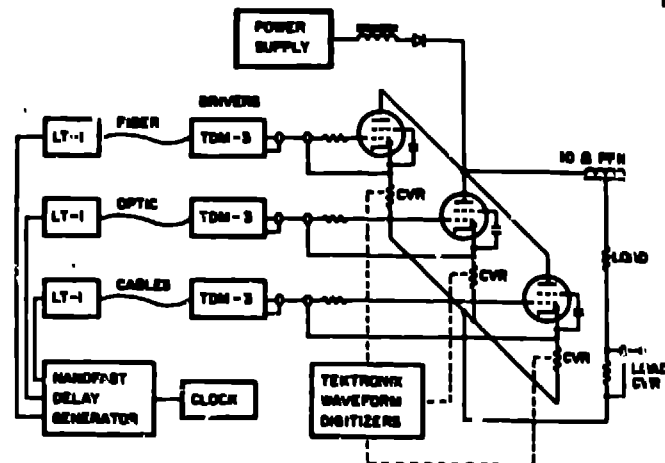


Fig. 3. A block diagram of the three-thyatron test circuit.

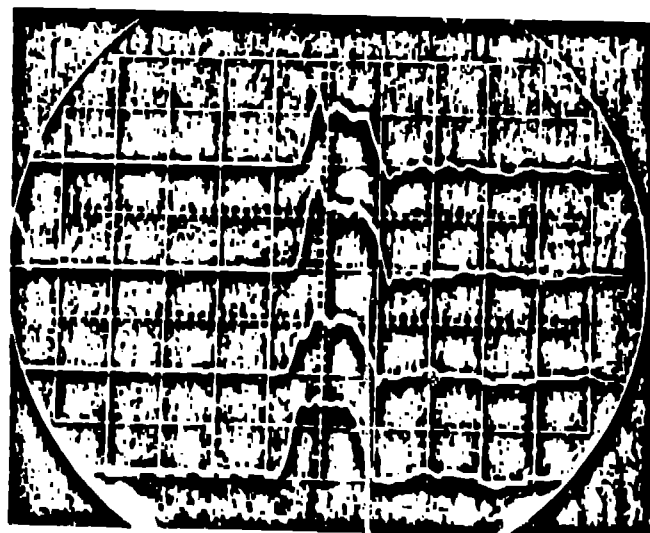


Fig. 4. Oscillogram of three tube current pulses. Top three traces - tube currents 200 A/div. Bottom trace - load current 500 A/div. Horiz - 100 ns/div.

TWO PARALLEL HY-3013 $e_{py} = 25$ kV $q_{py} = 1000$ pps $Z = 25 \Omega$			
	$di/dt$	CURRENT RISE TIME	PEAK CURRENT
TUBES	$2.1 \times 10^{11}$ A/s	20 ns	250 A
LOAD	$5.2 \times 10^{11}$ A/s	20 ns	1000 A
THREE PARALLEL HY-3013 $e_{py} = 25$ kV $q_{py} = 1000$ pps $Z = 10 \Omega$			
	$di/dt$	CURRENT RISE TIME	PEAK CURRENT
TUBES	$1.5 \times 10^{11}$ A/s	20 ns	400 A
LOAD	$5.5 \times 10^{11}$ A/s	20 ns	1200 A

Fig. 5. Current pulse parameters for both the two and three-tube modulators.

all tubes was within a 2-4 ns window. Conventional counter-type measurement techniques can at best give 20-ns resolution, which is far from the nanosecond resolution needed. Sophisticated analog frequency shift techniques can give the real time resolution required, but are extremely involved and expensive. Using waveform digitizers with computer control is a viable solution but also expensive.

A block diagram of the system devised to control the con commutation is shown in Fig. 6. This control technique is based on charge transfer rather than real-time current measurements. The common energy store (PFN) is charged to voltage  $V$  and corresponding charge  $Q$ . With three thyratrons, each should pass  $Q/3$  in the same amount of time if equal sharing is achieved. The output of the thyatron CVR is integrated (to give  $Q$ ), amplified and fed to a sample-and-hold. The sample-and-hold is triggered at a predetermined time during the current pulse and the value of  $Q$  is stored. A low speed A/D converter translates the value of  $Q$  to an 8-bit digital word. The microprocessor averages all the values of  $Q$  and subtracts each  $Q$  from the average. If the difference between the average and the measured  $Q$  is within predetermined range, the microprocessor does nothing. If the difference is out of tolerance in the negative direction, that particular thyatron is commutating too early and the microprocessor adjusts the programmable delay accordingly. Likewise, if the difference is out of tolerance in the positive direction, the tube was fired too late. Experiments show that delay adjustments in two nanosecond steps is adequate to force current sharing. Hybrid programmable delay minicircuits are available that can increment in 1 ns steps from 1 ns to 255 ns and in 2 ns steps from 1 ns to 530 ns. These programmable delays interface directly with the 8-bit output of many microprocessors.

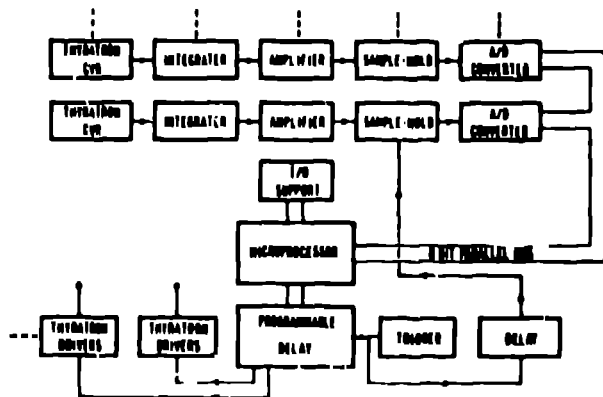


Fig. 6. Control system block diagram.

All development of the control circuitry has utilized the waveform digitizer for performing the integration, sample hold, and A/D functions and a PDP-11 has performed the microprocessor and programmable delay functions. The discrete integrator, sample-and-hold, and A/D portion of the control system has been built and tested but a complete system has not been completed.

#### Future Areas of Development

The successful operation of three hard parallel thyratrons makes the probability of using four or more tubes very good. Having reduced the impedance of the discharge circuit from 25  $\Omega$  (2 tubes) to 10  $\Omega$  (3 tubes) with no degradation in performance suggests development should be continued. Multiple uninterrupted 5-hour runs have proven the principle and stability of the system. Several characteristics of this system favor its use in applications where repetition rate and/or power agility are required as in high-energy laser systems or pulse-modulated power systems.

The next proposed step is to complete development of an integrated stand-alone control system for up to five parallel tubes. One suggested application involves construction of a fully-instrumented five-parallel thyatron-switched pulsed charged line in stripline geometry, possibly with an excimer laser load. Testing the system in an actual laser environment is most important to the development of a reliable control system.

#### Conclusion

Several methods for the control of hard-parallel thyratrons have been investigated and discussed. The most promising method of control developed so far seems to be accurate control of individual thyatron trigger timing. A method of using conventional analog and digital technology to implement a computer-controlled system is shown with hopes that a complete system can be demonstrated in the near future.

#### References

1. G. McDuff, "Parallel Operation of Thyratrons in Low Inductance Discharge Circuits," 3rd International Pulsed Power Conference, June 1981.
2. A. Litton, G. McDuff, "HY-3013 test data, unpublished, Los Alamos National Laboratory, 1981.